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## FINAL TECHNICAL REPORT

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UV, Visible, and Gravitational Astrophysics Research and Analysis Program

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### CALIBRATION OF POST-AGB SUPERGIANTS AS STANDARD EXTRAGALACTIC CANDLES FOR *HST*

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# Calibration of Post-AGB Stars as Standard Extragalactic Candles for *HST*

## Final Report

This report summarizes activities carried out with support from the NASA Ultraviolet, Visible, and Gravitational Astrophysics Research and Analysis Program. The Principal Investigator is Howard E. Bond (Space Telescope Science Institute). For the first two years the grant number was NAGW-4361, and for the final year it was NAG5-3912.

Postdoctoral Associate Laura K. Fullton was partially supported by this grant from her arrival at STScI in late 1995 until the end of the funded period in early 1998.

The aim of the program is to calibrate the absolute magnitudes of post-asymptotic-giant-branch (post-AGB or PAGB) stars, which we believe will be an excellent new “standard candle” for measuring extragalactic distances. The reason for this belief is that in old populations, the stars that are evolving through the PAGB region of the HR diagram arise from only a single main-sequence turnoff mass. In addition, the theoretical PAGB evolutionary tracks show that they evolve through this region at constant luminosity; hence the PAGB stars should have an extremely narrow luminosity function. Moreover, as the PAGB stars evolve through spectral types F and A (en route from the AGB to hot stellar remnants and white dwarfs), they have the highest luminosities attained by old stars (both bolometrically and in the visual band). Finally, the PAGB stars of these spectral types are very easily identified, due to their large Balmer jumps, which are due to their very low surface gravities.

Our observational approach is first to identify PAGB stars in Milky Way globular clusters and in other Local Group galaxies, which are at known distances, and thus to measure accurate absolute magnitudes for the PAGB stars. With this Milky Way and Local Group luminosity calibration, we will then be in a position to find PAGB stars in more distant galaxies from the ground, and ultimately from the *Hubble Space Telescope*, and thus derive distances. These PAGB stars are, as noted above, the *visually brightest members of Population II*, and thus will allow distance measurements to galaxies that do not contain Cepheids, such as elliptical galaxies, as well as distances to spirals using PAGB stars in their halos. Moreover, the method is entirely independent of Cepheids, and thus provides a direct test of the Cepheid distance scale.

Our observational technique is CCD photometry. We use the standard *BVI* filters, to which we add a Gunn *u* filter that measures the size of the Balmer jump. Basically, we identify stars that are blue in  $B - V$  and  $V - I$  (i.e., A-F stars), but “red” in  $u - B$  (i.e., having a large Balmer discontinuity).

During the funded research period, we received time allocations for five observing runs at the Kitt Peak 4-m telescope with its prime-focus CCD camera, but 3 out of those 5 runs were completely or nearly completely ruined by bad weather and excessive moonlight. Nevertheless, we were able to obtain at least some frames in nearly every member of the Local Group. During her stay at STScI, Fullton worked extensively on reducing the 4-m CCD frames. Results are outlined below.

In a separate aspect of the project, we have obtained CCD data at Cerro Tololo Inter-american Observatory, using a CCD camera on the 1.5-m telescope, to measure magnitudes and colors for PAGB stars in the Magellanic Clouds. The PI was awarded two observing runs, in January and October 1995. The target objects were stars selected by Bond on objective-prism material obtained earlier (in 1993) with the Curtis Schmidt telescope at CTIO.

With UVGA support, we also initiated a program aimed at surveying all of the Milky Way globular clusters for PAGB stars, with 0.9-m telescopes at KPNO and CTIO. We predict that there will be about a dozen A-F PAGB stars in the entire Milky Way globular-cluster system, which will play a crucial role in the luminosity calibration. This program got underway in September 1996 at Kitt Peak, and continued with successful KPNO 0.9-m runs in May and September 1997 and March 1998, and with Cerro Tololo 0.9-m runs in June and November 1997 and April 1998. At this writing, we have good CCD frames, generally reaching down to the horizontal branch, for some 90 Milky Way globular clusters. There are another  $\sim 20$  remaining clusters with  $V(\text{HB}) \leq 17$  (all of them in the Galactic bulge region) to observe in order to complete the  $uBVI$  survey of the entire Galactic globular-cluster system to that limit (see future plans below). To date, there are three well-established A-F PAGB stars in Milky Way globulars: one in  $\omega$  Centauri, and two in NGC 5986, and they in fact do show a very narrow range of luminosities averaging  $M_V = -3.4$ .

As described above, for purposes of identifying PAGB stars, we are developing a new “ $uBVI$ ” photometric system, based on the  $u$  filter of the Gunn-Thuan system combined with the standard  $BVI$  filters of the Johnson-Cousins system. The advantage of Gunn  $u$  over Johnson  $U$  is that the former filter’s bandpass is entirely below the Balmer discontinuity. PAGB stars, which are low-mass stars in transitory high-luminosity evolutionary stages, will have extremely low surface gravities, and hence, as they pass through spectral types F and A, will have very large Balmer jumps. This is the distinctive feature that gives them unique  $u - B$  colors, and allows PAGB stars to be detected readily throughout the Local Group. We have made extensive observations of Landolt standard stars, to which we are adding a calibration of the  $u$  filter, in order to develop a network of  $uBVI$  standards around the celestial equator.

Fullton completed a full-scale DAOPHOT photometric reduction of two  $16' \times 16'$  CCD fields in the halo of M31. By doing photometry of every detected star on the CCD chip, and selecting those with large  $u - B$  colors but blue  $B - V$ , we identified 15 candidate PAGB stars. Since we know how many M31 halo red giants there are in these fields (10,000 per field), the 15 stars give us a good estimate of their evolutionary lifetimes for comparison with theory. In fact, our derived lifetime of 20,000 yr is in superb agreement with the PAGB evolutionary track calculated in 1983 by Schönberner, for a stellar remnant mass of  $0.546 M_\odot$ .

The M31 PAGB counts indicate that the typical star in the M31 halo does *not* produce a planetary nebula (since there are far fewer planetary nebulae in the M31 halo than PAGB stars, in spite of very similar lifetimes). In work with George Jacoby of Kitt Peak National Observatory, Fullton has found that there are very few planetary nebulae in Milky Way globular clusters. Our findings in M31 are yet another indication that low-mass Population II stars do not produce planetaries, except in rare circumstances related to coalescence of binary stars (such as blue stragglers). The reason is simply the long transition time across the HR diagram: by the time the central star is hot enough to ionize the surrounding ejecta, the ejecta have long since dissipated into space.

The apparent magnitudes of the PAGB candidates in the halo of M31 have a small scatter,  $\sigma \simeq 0.3$  mag, in agreement with our expectation of a very narrow luminosity function. The error of the mean apparent magnitude is a very small  $\pm 0.06$  mag, and by applying our preliminary absolute calibration (based on the three PAGB stars in Milky Way globulars), we reproduce the Cepheid distance of M31 to within the errors.

By fitting the observed luminosities of our M31 PAGB stars to theoretical post-AGB tracks, we find that their masses average about  $0.53 M_\odot$ , in quite good agreement with

recent determinations of the masses of white dwarfs in Milky Way globular clusters. This is a gratifying confirmation of the expectation that white dwarfs are descended from post-AGB stars.

Our CCD observations of NGC 205, the well-known dwarf elliptical companion of M31, reveal a sequence of PAGB stars, but they are about 0.35 mag fainter than those in M31. This places NGC 205 17% further away than M31 itself (or about 120 kpc further away), a fairly startling result in view of the obvious tidal distortion of NGC 205 by M31. Most workers have heretofore assumed NGC 205 to be at the *same* distance as M31. This important measurement, made in just a few hours of 4-m time, demonstrates the power of our new method for measuring extragalactic distances.

Finally, an unexpected byproduct of our 0.9-m run at Kitt Peak in May 1997 was Bond's optical identification of the counterpart of the gamma-ray burst GRB 970508. The subsequent determination of an absorption-line redshift for the optical source resolved the 3-decade-old debate on the distance scale of gamma-ray bursts.

### Future Plans

The PI has received additional UVGA support in a new three-year grant (NASA NAG5-6821) to continue this program. An outstanding new Ph.D. in astrophysics, Dr. David Alves, joined this project as a postdoctoral fellow in December 1998. He has acquired considerable expertise in astronomical photometry during his thesis work, carried out at the University of California at Davis and at Lawrence Livermore National Laboratory, where he was associated with the MACHO project.

Dr. Alves' primary assignment will be to work on the extensive photometric data reductions needed for the impressive body of CCD observations acquired to date with NASA UVGA support. Alves and Bond will complete the establishment of the *uBVI* standard-star network, and then proceed to the reduction and calibration of the Milky Way cluster survey, Magellanic Cloud data, and the Local Group frames.

The ultimate aim of the program is (a) to determine the absolute magnitudes of PAGB stars and the metallicity dependence, if any, thus establishing a "Population II" distance scale that will be entirely independent of Cepheid variables; and (b) to use *HST* observations in elliptical galaxies and the halos of spirals, at distances larger than that of M81, to establish independent distances to these galaxies, and thus calibrate various secondary distance indicators. With the Advanced Camera and/or Wide Field Camera 3 on *HST*, we expect to be able to measure distances to as far out as the Virgo Cluster with great efficiency and accuracy, using our post-AGB standard candles.

### Publications

1. L. K. Fullton, H. E. Bond, A. Saha, and K. G. Schaefer  
"Post-AGB A and F Supergiants as Standard Candles"  
*Bull. A.A.S.*, **27**, 1293, 1995.
2. H. E. Bond  
"Post-AGB Stars as Standard Extragalactic Candles"  
In *The Extragalactic Distance Scale*, eds. M. Livio, M. Donahue, and N. Panagia (Cambridge: Cambridge University Press), p. 224, 1997.

3. H. E. Bond  
 "Post-AGB Stars as Extragalactic Candles"  
 In *Planetary Nebulae, IAU Symp. 180*, eds. H. Habing and H. Lamers (Dordrecht: Kluwer),  
 p. 460, 1997.
4. H. E. Bond, L. K. Fullton, and A. Saha  
 "Post-AGB A and F Supergiants as Extragalactic Candles"  
 Proceedings of the Third Conference on Faint Blue Stars, ed. A.G.D. Philip, J.W. Liebert,  
 and R.A. Saffer, p. 235, 1997.
5. L. K. Fullton, H. E. Bond, A. Saha, and R. A. Saffer  
 "Calibration of Post-AGB A and F Supergiants as Standard Candles"  
*Bull. A.A.S.*, **29**, 811, 1997.
6. H. E. Bond and L. K. Fullton  
 "Post-AGB Stars in the Halos of Nearby Galaxies"  
 AAS Topical Session on "Old Stellar Populations Beyond the Milky Way"  
*Bull. A.A.S.*, **29**, 843, 1997.
7. L. K. Fullton and H. E. Bond  
 "Post-AGB Stars in Local Group Galaxies"  
*Bull. A.A.S.*, **29**, 1243, 1997.
8. Discovery of Optical Counterpart of GRB 970508  
*IAU Circular*, No. 6654, 1997.
9. K. C. Sahu, M. Livio, L. Petro, H. E. Bond, F. D. Macchetto, T. J. Galama, P. J. Groot, J.  
 van Paradijs, and C. Kouveliotou  
 "Observations of GRB 970228 and GRB 970508, and the Neutron-Star Merger Model"  
*Astrophys. J. (Letters)*, **489**, L127, 1997.
10. H. E. Bond and L. K. Fullton  
 "Post-AGB Stars in the Halo of M31 and the Implied Masses of Halo White Dwarfs"  
 In Proceedings of the Eleventh European Conference on White Dwarfs, ed. J.-E. Solheim, in  
 press

# FEDERAL CASH TRANSACTION REPORT

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Name  
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## 3. FEDERAL EMPLOYER IDENTIFICATION NO.

**86-0138043**

Approved by Office of Management and Budget, No. 80-R0182

1. Federal sponsoring agency and organizational element of which this report is submitted

**NASA Goddard Space Flight Center**

**Accounting Branch Code 151-2**

**Greenbelt, MD 20771**

4. Federal grant or other identification number

**NAG5-3912**

6. Letter of credit number

**80005122**

5. Recipient's account number  
identification number

**J0533**

7. Last payment voucher number

**N/A**

Give total number for this period

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**\$41,660.68**

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TO **02/14/98**

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a. Cash on hand beginning of reporting period.	0.00
b. Letter of credit withdrawals - wire transfer	41,660.68
c. Treasury check payments	0.00
d. Total receipts (sum of lines b and c)	41,660.68
e. Total cash available (Sum of lines a and d)	41,660.68
f. Gross disbursements	41,660.68
g. Federal share of program income	0.00
h. Net disbursements (Line f minus line g)	41,660.68
i. Adjustments of prior periods	0.00
j. Cash on hand end of period	0.00

## 12. THE AMOUNT SHOW

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a. Interest income	0.00
b. Advances to subgrantees or subcontractors	0.00

## 14. REMARKS (Attach additional sheets of plain paper, if more space is required)

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TYPED OR PRINTED NAME AND TITLE

**MARIANNE W. JOHNSON/ACCOUNTING SPECIALIST**

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FEDERAL GRANT OR OTHER IDENTIFICATION NUMBER <i>(Show a subdivision by other identifying numbers if required by the Federal Sponsoring Agency)</i>	RECIPIENT ACCOUNT NUMBER OR OTHER IDENTIFYING NUMBER	FEDERAL SHARE OF NET DISBURSEMENTS	
		NET DISBURSEMENTS (Gross disbursements less program income received) FOR REPORTING PERIOD	CUMULATIVE NET DISBURSEMENTS
(a) NAG5-3912	(b) J0533	(c) 0.00	(d) 41,660.68

5. TOTALS (Should correspond with amounts shown on SF 272 as follows: column (c) the same as line 11h; column (d) the sum of lines 11h and 11i of this SF 272 and cumulative disbursements shown on last report. Attach explanation of any differences.)

272-201

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02/15/97

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Space Telescope Science Institute  
 Property 1018 Receive Report for Contract-Grant number  
 MAG5-3912  
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Contract/Grant	Tag No	Description	Model Number	Location	Date	PO	Comments
No records meeting the selection criteria found on the PROPERTY file.							



## Final Patent/Invention Report

Grant #: NAG5-3912 & NAGW-4361

Title: *Calibration of Post-Age Supergiants as Standard Extragalactic Candles for HST*

Principal Investigator: Dr. Howard Bond

No patents or inventions resulted from this grant.